CHANNELS AND CHALLANGES:

HIGGS PHYSICS AT THE LHC

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- the puzzle of mass & the Higgs Boson
- challenge: Standard Model Higgs
- challenge: not quite Standard Model Higgs
- why we will be fine

PARTICLES AND MASSES

Standard Model: matter particles — fermions

definition of 'mass':
inertia in TV tube,
dropping in LEP ring
1 GeV $\equiv$ proton mass

- three leptons [essentially means 'like electron']
  1897 Thomson: electron$^{(1)}$ $m_e = 0.5$ MeV
  1937 Anderson: muon$^{(2)}$ $m_\mu = 106$ MeV
  1975 Perl: tau lepton$^{(3)}$ $m_\tau = 1800$ MeV
- three neutrinos ν
  1990s CERN: no more than 3 light neutrinos [masses yet unknown]
- six quarks [essentially means 'matter, but not like electron at all']
  neutron (uud) and proton (udd): up$^{(1)}$ and down$^{(1)}$
  bound states: strange$^{(2)}$, charm$^{(2)}$ and bottom$^{(3)}$ $m_b = 4.6$ GeV
  1995 Fermilab: top$^{(3)}$ $m_t = 175$ GeV

$\Rightarrow$ three generations of fermions, different in mass, first generation real life

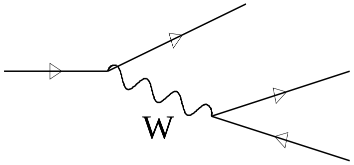
Mixing of generations

- quarks mix a little (Cabbibo–Kobayashi–Maskawa matrix)
  $\rightarrow$ one complex phase in 3×3 mixing matrix $\rightarrow$ 'CP violating effect' observed
- leptons mix a lot (Maki–Nakagawa–Sakata matrix)
  $\rightarrow$ CP violation not yet observed

INTERACTIONS AND MASS

Standard Model: interactions — bosons

- Rutherford 1911: electrons and protons/neutrons compose matter
  $\longrightarrow$ proton mass multiparticle effect
  $\longrightarrow$ electron mass zero
- electromagnetic and gravitational interactions
  $\longrightarrow$ forces with infinite range [Coulomb potential $V \propto 1/r$]
  $\longrightarrow$ equivalent to massless (virtual) photon exchange
- Fermi 1934: theory of weak interactions [$n \to pe^- \bar{\nu}_e$ and $\mu \to e^- \bar{\nu}_e \nu_\mu$]
  $\longrightarrow$ divergent four fermion reaction amplitude: $\mathcal{A} \propto G_F E^2$
  $\longrightarrow$ unitarity violation [transition probability $\propto |\mathcal{A}|^2$]
  $\longrightarrow$ 'effective theory' valid for $E < 600$ GeV
- Yukawa 1935: massive virtual particle exchange
  $\longrightarrow$ Fermi's theory for $E \ll M$
  $\longrightarrow$ unitary for large energies: $\mathcal{A} \propto g^2 E^2/(E^2 - M^2)$
  $\longrightarrow$ what does mass M mean for Yukawa particles?



- CERN 1983: W, Z bosons discovered
  $\longrightarrow$ $m_W \sim 80$ GeV and $m_Z \sim 91$ GeV [$m_{W,Z} \sim (m_t + m_b)/2$]
  $\longrightarrow$ mass: inertia when pushed, dropping to the ground in flight

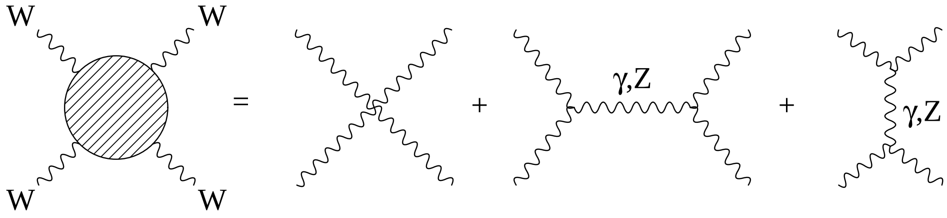
$\Rightarrow$ boson and fermion masses the same thing

UNITARITY AND THE HIGGS

Theory of W, Z bosons

- start with $SU(2)$ gauge theory [like QED with massless W, Z]
- include measured masses $\mathcal{L} \sim -m_{W,Z} A_\mu A^\mu$
  $\longrightarrow$ not gauge invariant [except in small $m_{W,Z}$ limit]
  $\longrightarrow$ not renormalizable [means not predictive to all energy scales]
  $\longrightarrow$ valid effective theory of massive W, Z bosons

Unitarity

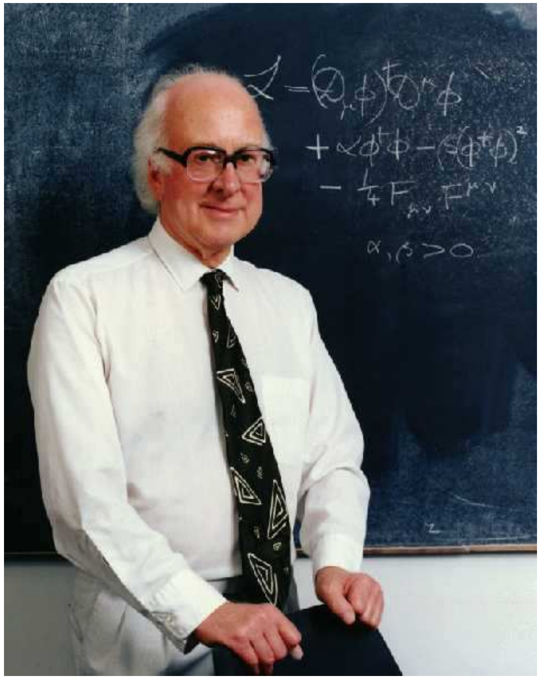


- test theory in $WW \to WW$ scattering
  $\longrightarrow \mathcal{A} \propto G_F E^2$ just like Fermi's theory, not unitary above 1.2 TeV [LHC energy!]
  $\longrightarrow$ postulate additional scalar Higgs boson to conserve unitarity
  $\longrightarrow$ fixed coupling $g_{WWH} \propto m_W$
- add fermions and test $WW \to f\bar{f}$
  $\longrightarrow$ fixed coupling $g_{ffH} \propto m_f$
- test new theory in $WW \to WWH$
  $\longrightarrow$ fixed coupling $g_{HHH} \propto m_H^2/m_W$
- final test: $WW \to HHH$
  $\longrightarrow$ fixed coupling $g_{HHHH} \propto m_H^2/m_W^2$

THE PUZZLE OF MASS AND THE HIGGS AT THE LHC

What we are going to look for at LHC:

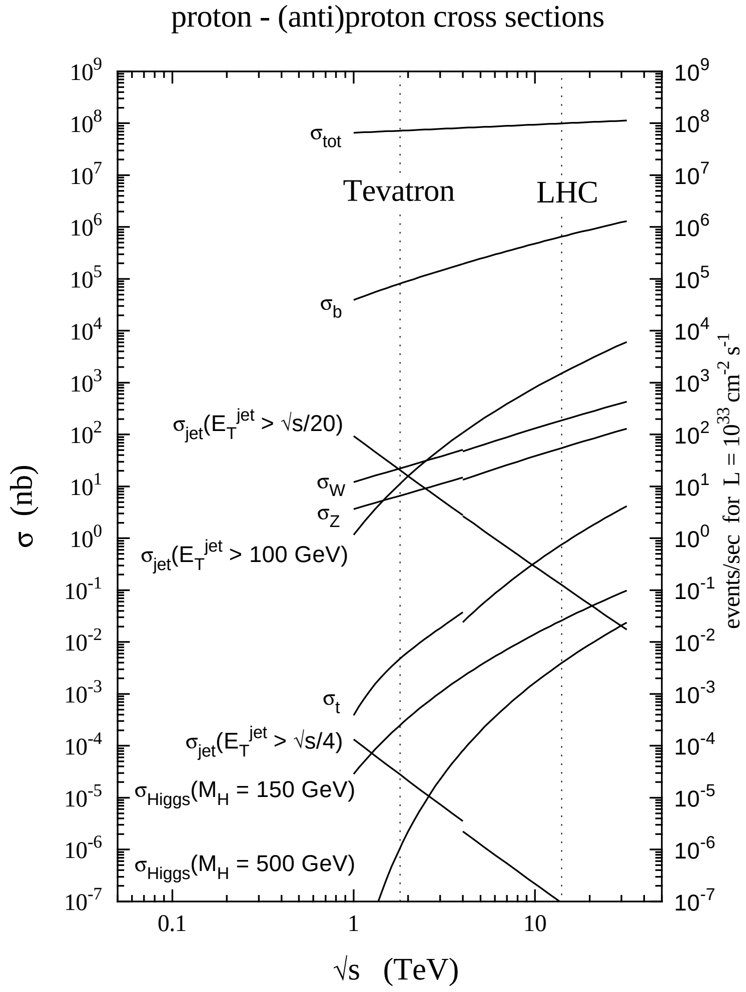
- electroweak gauge theory with massive W, Z bosons and a Higgs boson
- Higgs couplings to other particles fixed [proportional to particle masses]
- Higgs self coupling fixed [important for potential interpretation of Lagrangean]
- Higgs mass unknown [LEP data points to around 120 GeV]
- or unitarity violation effects at TeV scale [strongly interacting WW]



HADRON COLLIDERS: TEVATRON & LHC

Conversion of energy into mass [$E = mc^2$ with c=1]

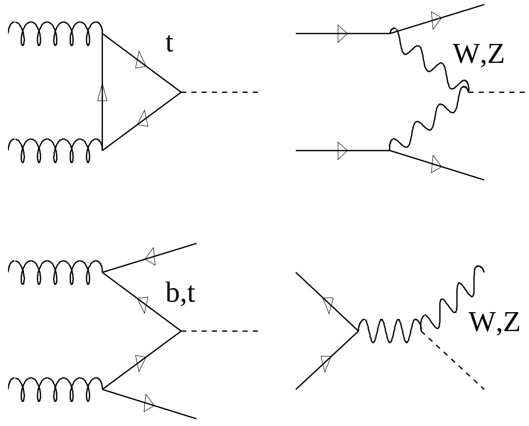
- search for new particles [easier if real particle produced]
  $\longrightarrow$ highest possible energies required
- electron colliders: collide two highly relativistic e
  LEP: 46 GeV each to produce Z
  LEP2: 103 GeV each for e.g. ZH
  ILC/CLIC: 1...4 TeV in the future
- hadron colliders: collide (anti)protons
  Tevatron: $p\bar{p}$ collision with 2 TeV [valence quarks]
  LHC: pp collisions with 14 TeV [gluons]
- LHC mass reach $\sim$ 3 TeV [trade luminosity for energy]



New physics with hadron colliders

- what is a jet and what is inside? [bottom tag, τ tag]
- trigger: ‘no leptons — no data’ [e.g. $pp \to t\bar{t} \to$jets]
- backgrounds rates $pp \to jj$ or $pp \to WZ$+jets
- statistical significance: $S/\sqrt{B} > 5$ is discovery

CHALLENGE 1: FIND STANDARD MODEL HIGGS



Design Higgs searches for the LHC

- (a) unitarity limit: $m_H < 1$ TeV
  (b) electroweak precision tests: $m_H < 220$ GeV
- production and decay of light Higgs

$gg \to H$
$qq \to qqH$
$gg \to t\bar{t}H$
$q\bar{q}' \to WH$

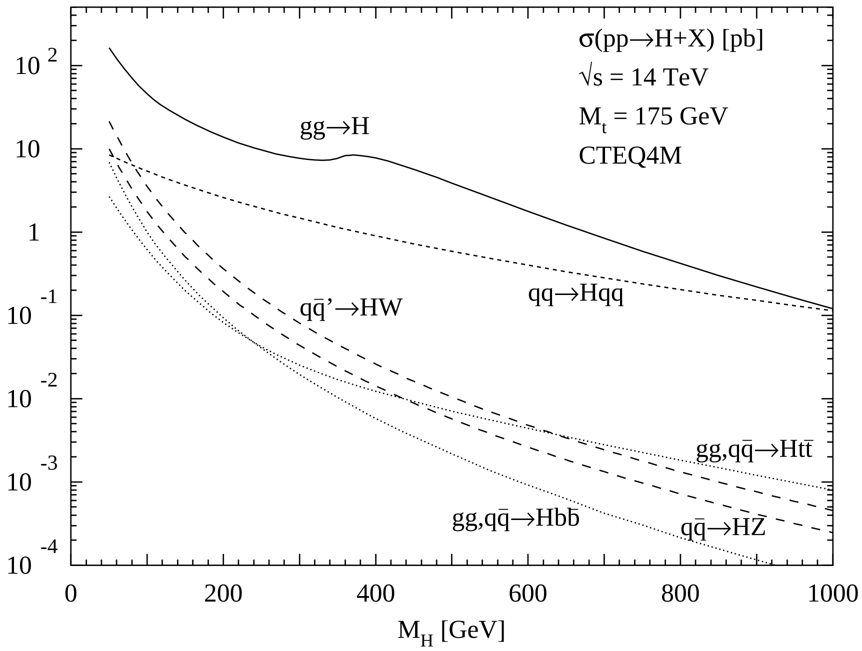
↔

signal × trigger
backgrounds
systematics
$S/\sqrt{B}$ vs. S/B
mass resolution...

↔

$H \to b\bar{b}$
$H \to WW$
$H \to \tau^+_{\ell h}\tau^-_{\ell}$
$H \to \gamma\gamma$
$H \to \mu\mu$...

Production rates



CHALLENGE 1: FIND STANDARD MODEL HIGGS

The numbers behind it

- 6 million Higgses in gluon fusion: $gg \to H \to \gamma\gamma$

  [mass resulution $\Delta m_H / m_H \sim \Gamma/\sqrt{S} < 0.5\%$]

- backgrounds smaller in WW fusion: $qq \to qqH \to qq\tau\tau$ [PRD 61 (2000)]

  [reconstruct $m_{\tau\tau}$ in collinear approximation, $S/B = \mathcal{O}(1)$]

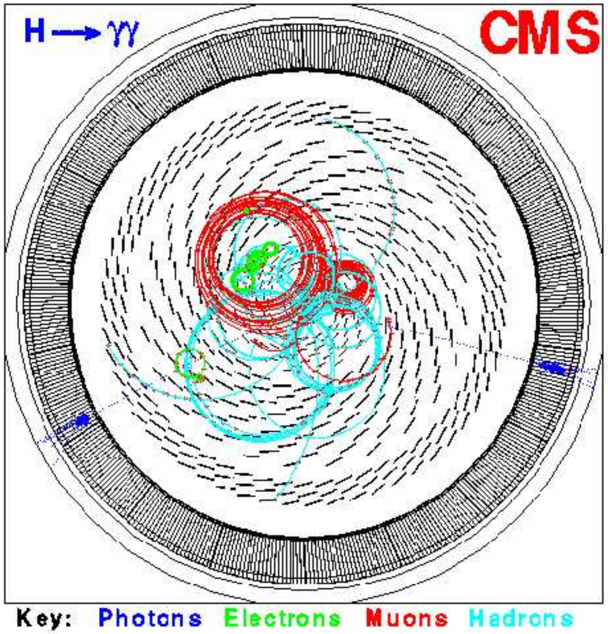
- off-shell Higgs decays: $qq \to qqH \to qqWW$ [PLB 503 (2001)]

  [works down to $m_H < 120$ GeV]

- few examples of challenging strategies:

  $gg \to t\bar{t}H \to t\bar{t}b\bar{b}$ [complexity of signal]
  $gg \to t\bar{t}H \to t\bar{t}\tau\tau$ [yet unclear]
  $q\bar{q}' \to WH \to Wb\bar{b}$ [backgrounds]
  $qq \to qqH \to qqb\bar{b}$ [no ATLAS trigger]

$\Rightarrow$ how many couplings can we extract?



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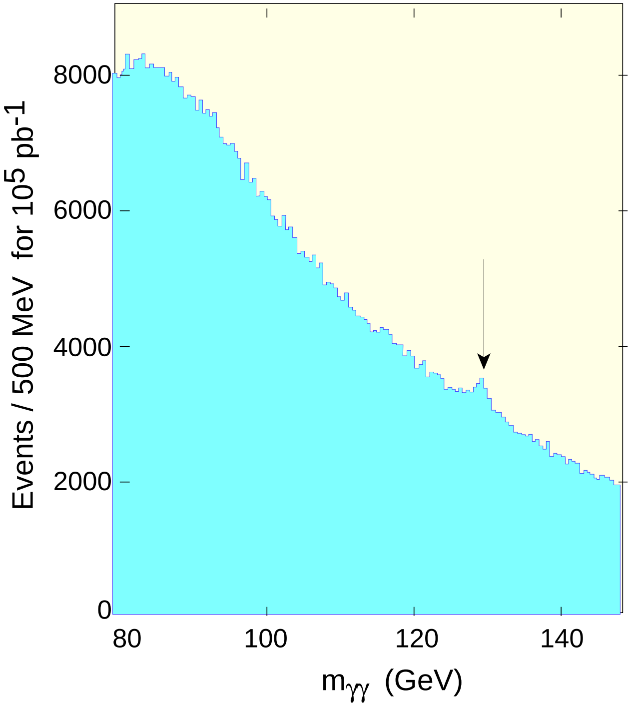
$H_{SM} \longrightarrow \gamma\gamma$



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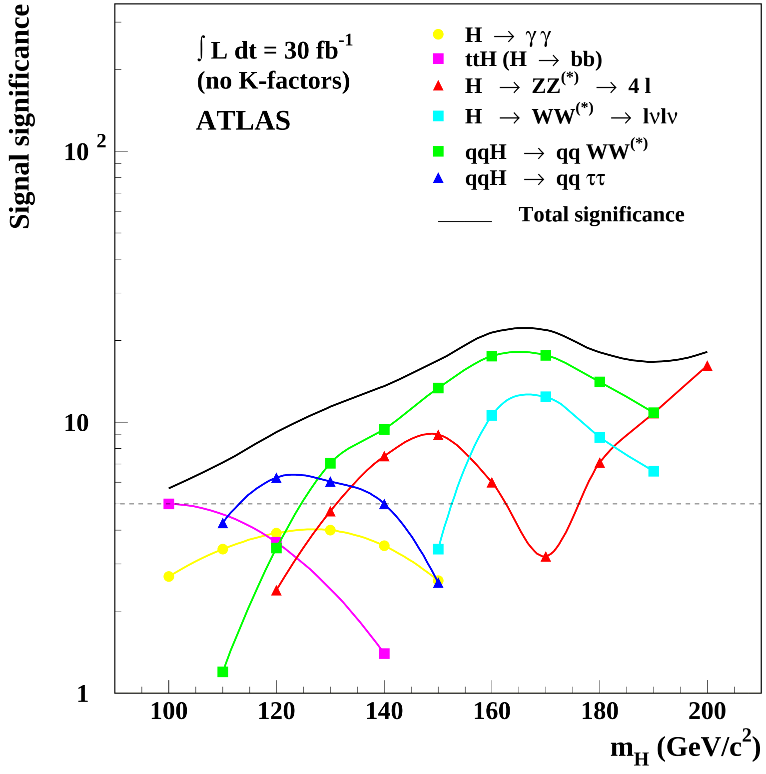


CHALLENGE 2: HIGGS POTENTIAL

Higgs Self Coupling

- scalar with Yukawa couplings to fermions, so what?
- back to Higgs potential: $V(H) = \frac{m_H^2}{2} H^2 + \frac{m_H^2}{2v} H^3 + \frac{m_H^2}{8v^2} H^4$

⇒ self couplings the holy grail of Higgs physics $\lambda = m_H^2/(2v^2)$

Higgs pair production [PRL 89 (2002),PRD 67 (2003),PRD 68 (2003)]

- $HH \to 4W$: serious detector simulation needed, not hopeless

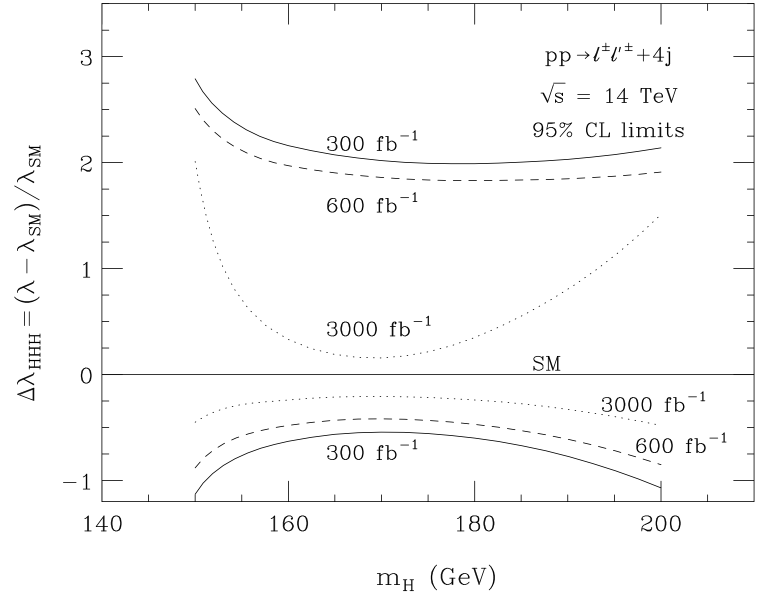
  [use observable m_{vis} to determine λ_{HHH}]
- $HH \to b\bar{b}\tau\tau$: miracle required
- $HH \to 4b$: several major miracles mandatory

  [ILC in better shape]
- $HH \to b\bar{b}\mu\mu$: small miracle would be helpful

  [might come out of $\mu\mu$ mass resolution]
- $HH \to b\bar{b}\gamma\gamma$: some enhancement needed

⇒ serious challenge to detectors and machine

[my personal favorite for luminosity upgrade]



SUPERSYMMETRIC HIGGS SECTOR

Why Supersymmetry?

- divergent one-loop corrections to m_H: $\delta m_H^2 \propto \Lambda^2 \; \left(2m_W^2 + m_Z^2 + m_H^2 - 4m_t^2\right)$
- Higgs mass always driven to cutoff scale [except Veltman's condition]
- invent theory with mirror particles which enter above with (-1)
  → remember spin–statistics: change spin by 1/2
  → call it supersymmetry → stabilize proton → explain dark matter ...

Required by Supersymmetry: two Higgs doublet model

- one (complex) Higgs doublet: 4 degrees of freedom
  → three for longitudinal W, Z, one for scalar Higgs
- two Higgs doublet: 8 degrees of freedom
  → three for longitudinal W, Z, five for Higgs particles
  → scalars h^0, H^0, pseudoscalar A^0, charged $H^\pm$
- free parameters
  (1) still only one free mass scale: m_A
  (2) two vacuum expectation values: $\tan\beta = v_t/v_b$

⇒ prediction: $m_h < 135$ GeV

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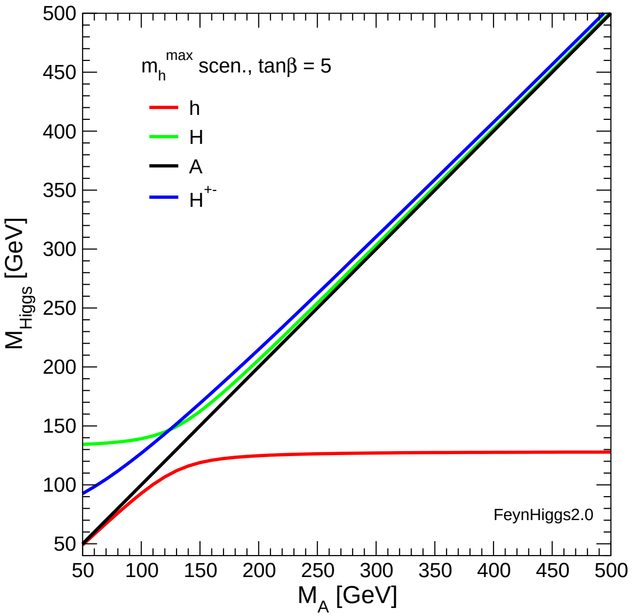


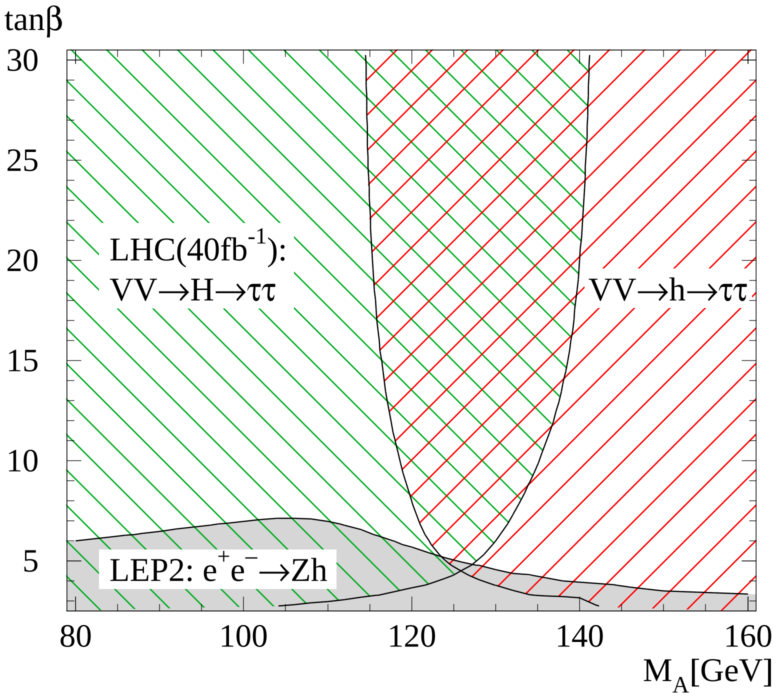
CHALLENGE 3: FIND ONE SUPERSYMMETRIC HIGGS BOSON

Supersymmetric Higgs bosons and $qq \to qqH \to qq\tau\tau$

- allowed light Higgs mass: $m_Z \ll m_h < 135$ GeV
- ‘decoupling regime’ $m_A \gtrsim 160$ GeV
  $\to A^0, H^0, H^\pm$ heavy
  $\to h^0$ looks like SM Higgs [of corresponding mass]
  $\to$ production rate: g_{WWh} like SM
  $\to$ branching fraction: $BR(h^0 \to \tau\tau) > BR(H_{\rm SM} \to \tau\tau)$
  $\to qq \to qqh^0 \to qq\tau\tau$ better than SM
- opposite case $m_A \lesssim 120$ GeV
  $\to H^0$ around 135 GeV
  $\to qq \to qqH^0 \to qq\tau\tau$ as in SM
- intermediate case $m_A \sim 120$ GeV
  $\to h^0, H^0 \to \tau\tau$ just add up

$\Rightarrow$ No-lose theorem: $qq \to qq\{h^0, H^0\} \to qq\tau\tau$

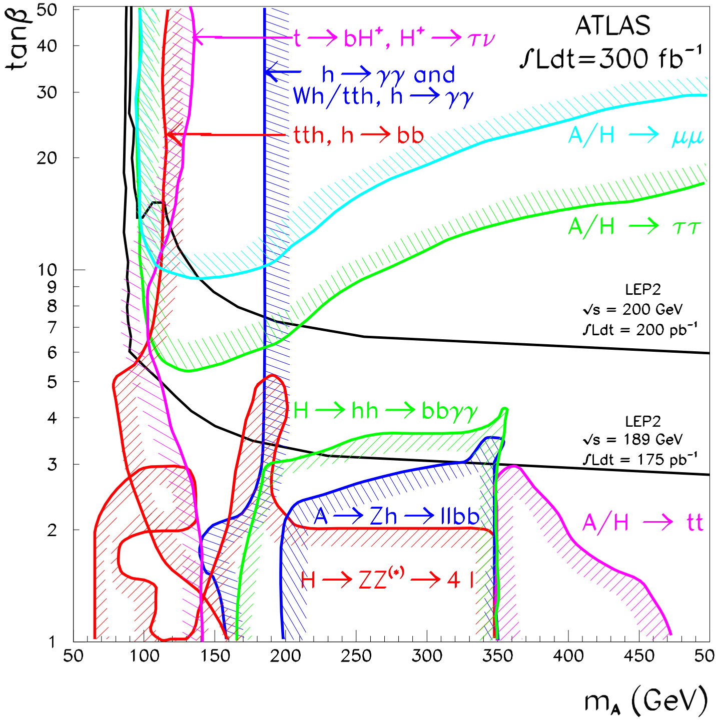
[PLB 454 (1999)]



CHALLENGE 4: MORE SUPERSYMMETRIC HIGGS BOSONS

Tell it is two Higgs doublets: find more Higgses [PRD 67 (2003),PRD 69 (2004),hep-ph/0503135]

- intermediate $m_A \sim 120$ GeV:
  $\longrightarrow$ lots of Higgs bosons h^0, H^0, A^0 observable
  $\longrightarrow$ problem distinguishing them: $H^0 \to \mu\mu$
  $\longrightarrow$ top quark decays $t \to bH^+$? [Tevatron RunI top sample still small]
- decoupling regime $m_A \gtrsim 160$ GeV
  $\longrightarrow$ light SM like h^0 guaranteed
  $\longrightarrow$ Yukawa coupling for $H^0, A^0, H^\pm$: $m_b \tan\beta$ and $m_t/\tan\beta$
  $\longrightarrow$ $\tan\beta < 20$? [possibly $gg \to H^0 \to h^0 h^0$]
- $m_A \gtrsim 160$ GeV and $\tan\beta > 20$
  $\longrightarrow$ bottom Yukawa coupling $m_b \tan\beta \gtrsim 100$ GeV
  $\longrightarrow$ production e.g. $b\bar{b} \to H^0$ or $gb \to tH^-$
  $\longrightarrow$ decays e.g. $H^0 \to \tau\tau, \mu\mu$ or $H^- \to \tau\bar{\nu}$
  $\longrightarrow$ supersymmetry:
  $m_b/(1-\Delta_b)$ with $\Delta_b \propto \mu m_{\tilde{g}}/M^2_{\text{SUSY}}$



OUTLOOK

Why we will be fine at the LHC

- if there is no Higgs boson there will be unitarity violation
- the (light) Standard Model Higgs will appears in several channels
- we will be able to measure many Higgs properties

- in supersymmetric models we will find one Higgs boson
- in supersymmetric models we should find even more of them

- there have been many futile attempt to hide the Higgs at the LHC
- and then ILC can do many things even better

⇒ exciting LHC times lie ahead of us